

Composite Higgs Working Group: RS Benchmarks

Martin Bauer

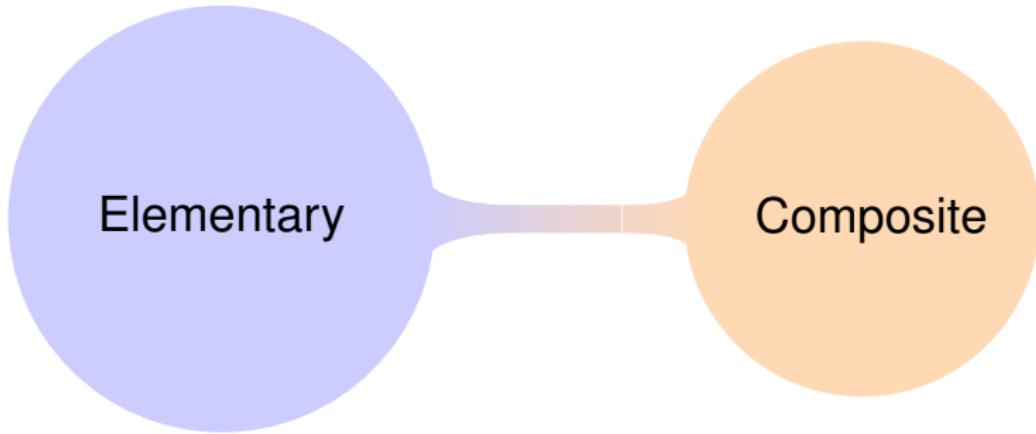
① Composite Higgs Models

② RS Models

③ Benchmarks

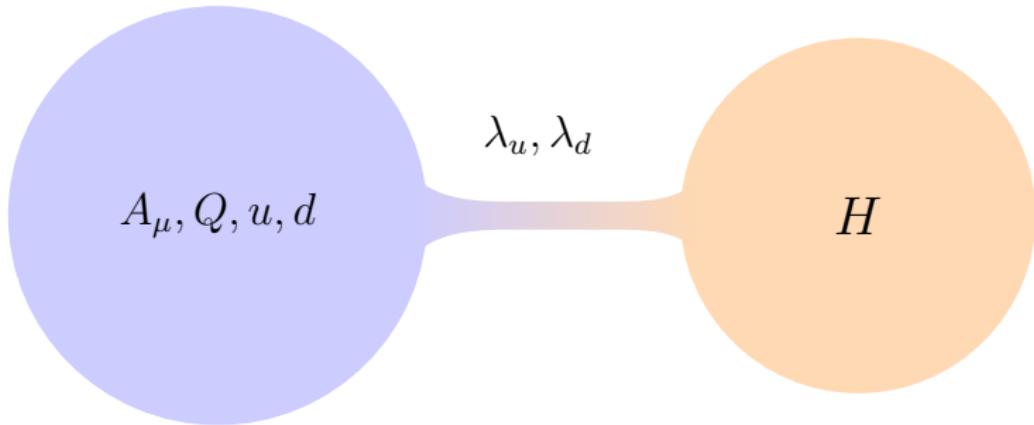
④ Flavor Physics in the RS Model

COMPOSITE HIGGS MODELS



COMPOSITE HIGGS MODELS

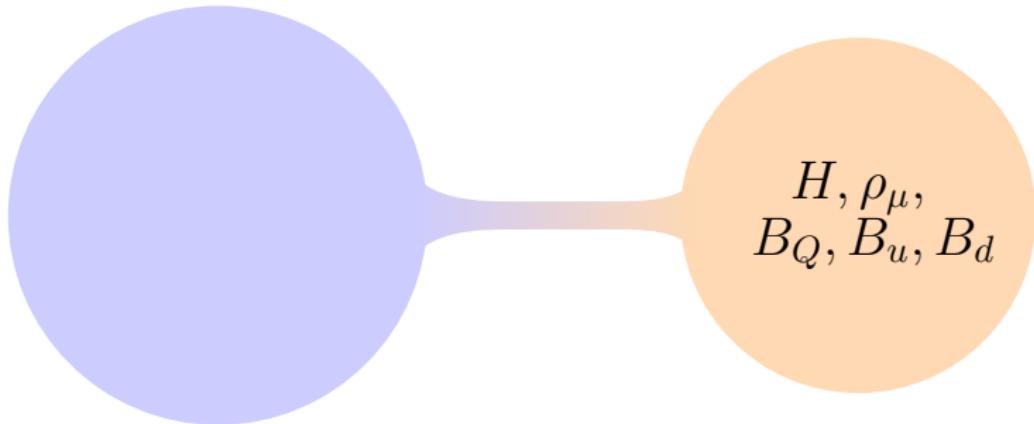
Technicolor, ETC, CTC



$$\mathcal{L} = \mathcal{L}_{\text{el}} + \lambda_u \bar{Q} H u + \lambda_d \bar{Q} H^* d - V(H)$$

COMPOSITE HIGGS MODELS

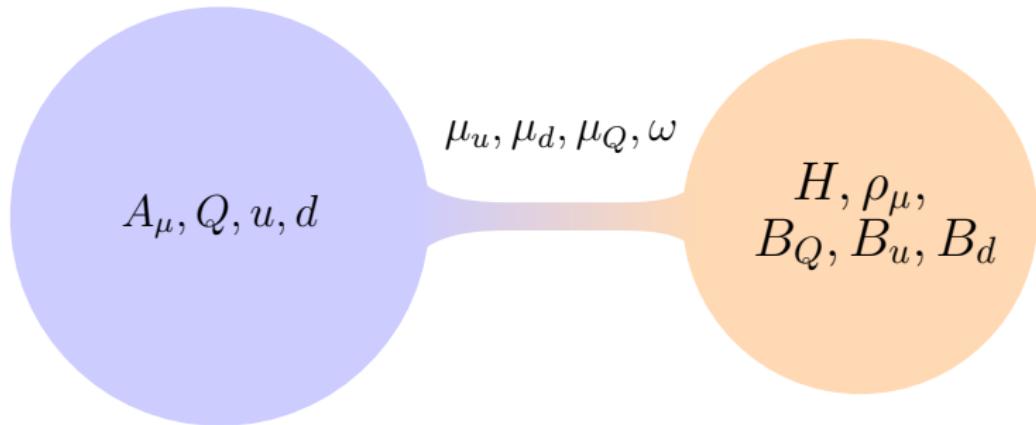
Total Compositeness (RS1)



$$\mathcal{L} = \mathcal{L}_{\text{comp}}$$

COMPOSITE HIGGS MODELS

Partial Compositeness (RS1)



$$\mathcal{L} \ni \mathcal{L}_{\text{el}} + \omega A_\mu \rho^\mu + \mu_u \bar{u} B_u + \mu_d \bar{d} B_d + \mu_Q \bar{Q} B_Q + \mathcal{L}_{\text{comp.}}$$

COMPOSITE HIGGS MODELS

Partial Compositeness: Mass generation

$$\mathcal{L} \ni \mathcal{L}_{\text{el}} + \mu_q \bar{q}_L B_R - m_B \bar{B} B + \bar{B}_L (\lambda H B_R^c) .$$

Rotating to the mass eigenbasis

$$\begin{pmatrix} q_L \\ B_L \end{pmatrix} = \begin{pmatrix} \cos \varphi_L & -\sin \varphi_L \\ \sin \varphi_L & \cos \varphi_L \end{pmatrix} \begin{pmatrix} \psi_L \\ \chi_L \end{pmatrix}, \quad \tan \varphi_L = \frac{\mu_q}{m_B}$$

leads to

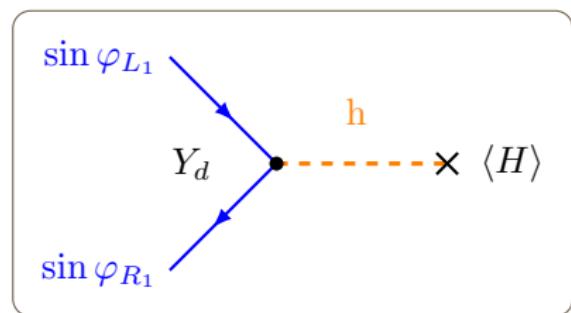
$$\mathcal{L} \ni -m_\chi \bar{\chi} \chi + (\bar{\psi}_L \sin \varphi_L + \bar{\chi}_L \cos \varphi_L) \lambda H (\psi_R \sin \varphi_R + \chi_R^c \cos \varphi_R) .$$

Couplings to vector mesons read

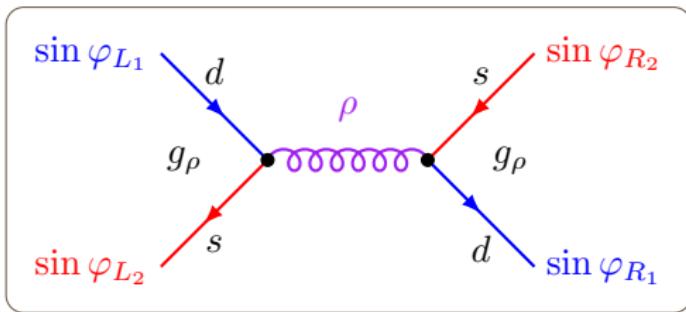
$$\mathcal{L} \ni g_\rho \bar{B} \not{\partial} B \longrightarrow g_\rho \sin \varphi_L^2 \bar{\psi}_L \not{\partial} \psi_L + g_\rho \sin \varphi_R^2 \bar{\psi}_R \not{\partial} \psi_R ,$$

COMPOSITE HIGGS MODELS

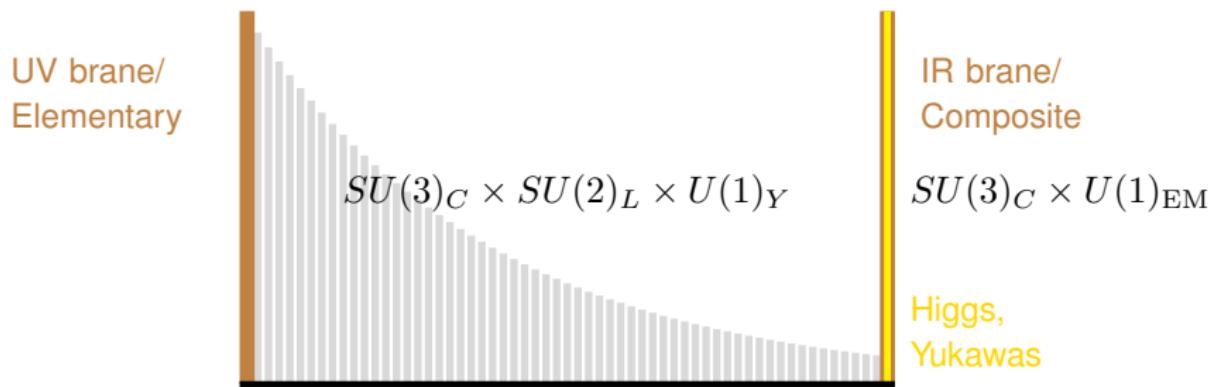
$$\begin{aligned} m_d &\sim \frac{v}{\sqrt{2}} \sin \varphi_{L_1} \lambda \sin \varphi_{R_1} \\ &\sim \frac{v}{\sqrt{2}} Y_d^{\text{eff}} \end{aligned}$$



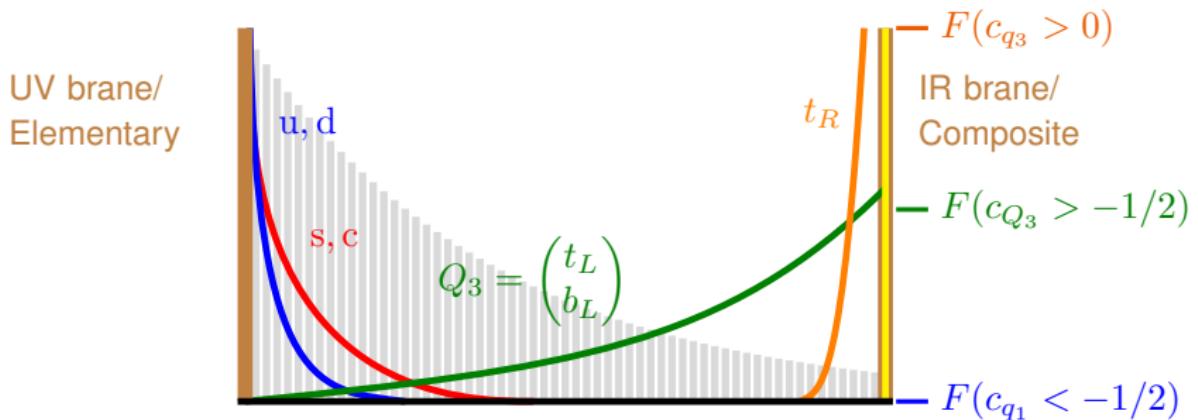
$$\begin{aligned} \frac{g_\rho^2}{M_{\text{KK}}^2} \sin \varphi_{L_1} \sin \varphi_{R_1} \sin \varphi_{L_2} \sin \varphi_{R_2} \\ \sim \frac{g_\rho^2}{M_{\text{KK}}^2} \frac{2m_d m_s}{(v\lambda)^2} \end{aligned}$$



RS MODELS

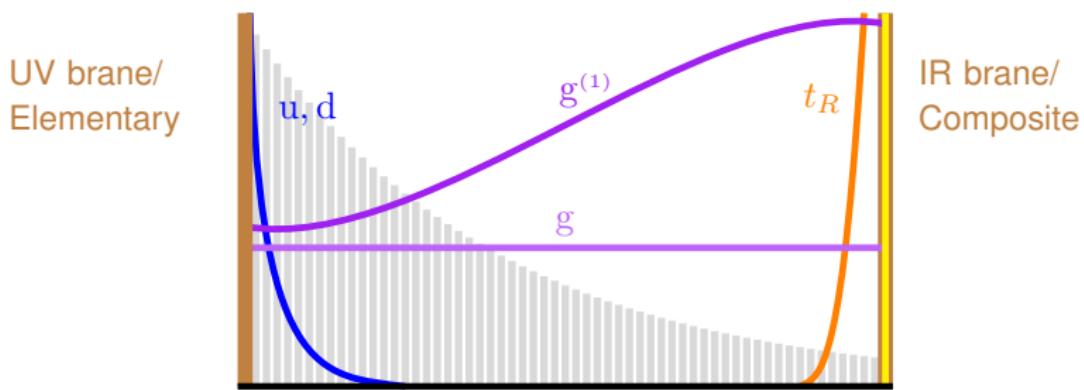


RS MODELS



$$F(c) \approx \begin{cases} \left(\frac{TeV}{M_{Pl}}\right)^{-(\frac{1}{2}+c)}, & c < -\frac{1}{2} \\ \sqrt{1+2c}, & c > -\frac{1}{2} \end{cases}$$

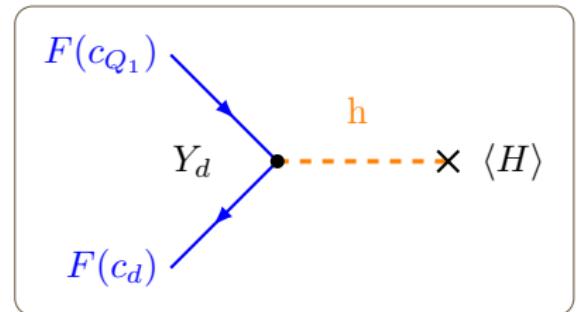
RS MODELS



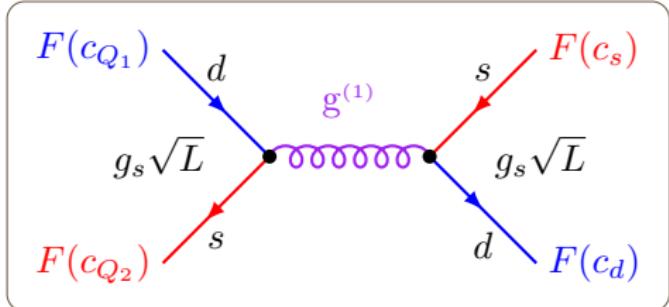
RS MODELS

The same parameters, which generate the masses of the light quarks suppress contributions to FCNCs: RS-GIM.

$$\begin{aligned} m_d &\sim \frac{v}{\sqrt{2}} F(c_{Q_1}) Y_d^{(5D)} F(c_d) \\ &\sim \frac{v}{\sqrt{2}} Y_d^{\text{eff}} \end{aligned}$$



$$\begin{aligned} &\frac{g_s^2 L}{M_{\text{KK}}^2} F(c_{Q_1}) F(c_d) F(c_{Q_2}) F(c_s) \\ &\sim \frac{g_s^2}{M_{\text{KK}}^2} L \frac{2m_d m_s}{\left(v Y_d^{(5D)}\right)^2} \end{aligned}$$



RS MODELS

Composite Higgs

Warped Geometry (RS)

(Large N) CFT with a confining phase below Λ	\leftrightarrow	Anti de Sitter space with an IR brane at $1/\Lambda$
Amount of Compositeness: $\sin \varphi_q$	\leftrightarrow	Localization in the ED: $F(c_q)$
Global symmetry in the strongly coupled sector	\leftrightarrow	Gauge symmetry in the bulk
Composite vector mesons (baryons)	\leftrightarrow	Gauge boson (quark) KK Modes

BENCHMARKS

What parameters describe (the flavor sector of) a composite Higgs model?

Parameters

- Compositeness scale Λ_{comp}
- 9 Quark localization parameters
 $c_{Q_1}, c_{Q_2}, c_{Q_3}, c_d, c_s, c_b, c_u, c_c, c_t$
- 2 Yukawa matrices Y_u, Y_d

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 $c_{Q_1}, c_{Q_2}, c_{Q_3}, c_d, c_s, c_b, c_u, c_c, c_t$ 

8 are fixed by the six quark masses and two of the Wolfenstein parameters
- 2 Yukawa matrices Y_u, Y_d

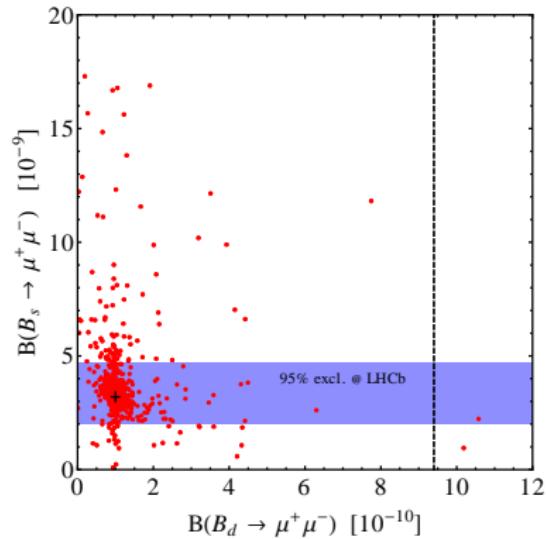
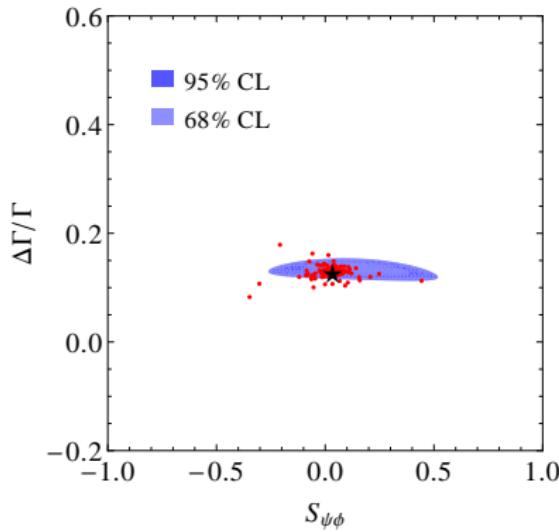
BENCHMARKS

What parameters describe (the flavor sector of) a composite Higgs model?

Parameters	Benchmark Example
• Compositeness scale Λ_{comp}	$\Lambda_{\text{comp}} = 1.367 \text{ TeV}$
• 9 Quark localization parameters $c_{Q_1}, c_{Q_2}, c_{Q_3}, c_d, c_s, c_b, c_u, c_c, c_t$	$c_Q = (-0.649399, -0.555219, -0.448969)$ $c_d = (-0.644379, -0.648314, -0.5904)$ $c_u = (-0.686149, -0.505565, 0.252274)$
• 2 Yukawa matrices Y_u, Y_d	$Y_u = \begin{pmatrix} -0.307 & 1.09 & 0.615 \\ -0.445 & 0.236 & -0.666 \\ 2.30 & 0.0259 & -1.83 \end{pmatrix} + i \begin{pmatrix} -2.25 & 2.01 & -0.359 \\ -0.741 & -0.441 & -0.120 \\ 0.870 & -0.030 & -0.877 \end{pmatrix}$ $Y_d = \begin{pmatrix} 0.576 & 1.89 & 2.41 \\ -2.3 & 2.78 & 0.284 \\ 0.109 & 0.485 & 2.36 \end{pmatrix} + i \begin{pmatrix} 1.28 & 1.32 & 0.916 \\ -1.33 & -0.792 & -0.427 \\ 0.199 & 0.0725 & -1.01 \end{pmatrix}$

FLAVOR PHYSICS IN THE RS MODEL

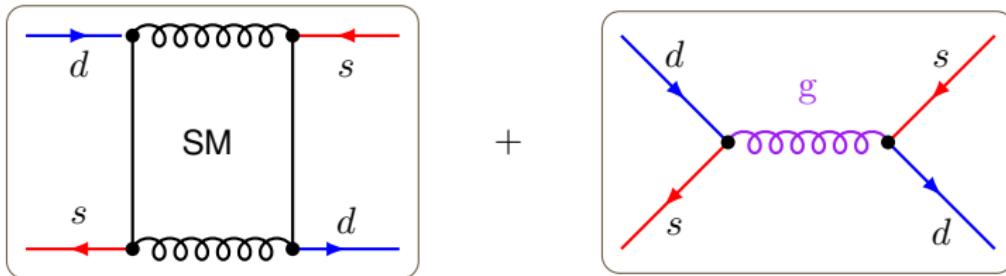
Large mixing angles suggest large effects in observables which are sensitive to couplings of third generation quarks.



FLAVOR PHYSICS IN THE RS MODEL

The RS-GIM mechanism is extremely effective, apart from one observable,

$$\epsilon_K = \frac{\kappa_\epsilon e^{i\phi_\epsilon}}{\sqrt{2}(\Delta m_K)_{\text{exp}}} \text{Im} \langle K^0 | \mathcal{H}_{\text{eff}}^{\Delta S=2} | \bar{K}^0 \rangle,$$



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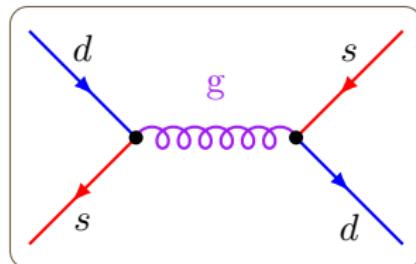
$$\epsilon_K = \frac{\kappa_\epsilon e^{i\phi_\epsilon}}{\sqrt{2}(\Delta m_K)_{\text{exp}}} \text{Im} \langle K^0 | \mathcal{H}_{\text{eff}}^{\Delta S=2} | \bar{K}^0 \rangle,$$

$$Q_1^{sd} = (\bar{d}_L \gamma^\mu s_L) (\bar{d}_L \gamma_\mu s_L)$$

$$\tilde{Q}_1^{sd} = (\bar{d}_R \gamma^\mu s_R) (\bar{d}_R \gamma_\mu s_R)$$

$$Q_4^{sd} = -\frac{1}{2} (\bar{d}_R^\alpha \gamma^\mu s_R^\beta) (\bar{d}_L^\beta \gamma_\mu s_L^\alpha)$$

$$Q_5^{sd} = -\frac{1}{2} (\bar{d}_R \gamma^\mu s_R) (\bar{d}_L \gamma_\mu s_L)$$



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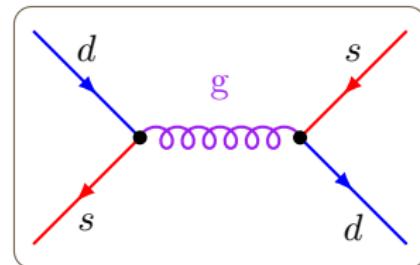
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$$\langle K^0 | \mathcal{H}_{\text{RS}}^{\Delta S=2} | \bar{K}^0 \rangle \propto C_1^{\text{SM+RS}} + \tilde{C}_1^{\text{RS}} + 100 \left(C_4^{\text{RS}} + \frac{1}{N_C} C_5^{\text{RS}} \right)$$

$$\text{Large chiral enhancement} \sim \left(\frac{m_K}{m_s + m_d} \right)^2$$

RGE running
3 TeV → 2 GeV

FLAVOR PHYSICS IN THE RS MODEL

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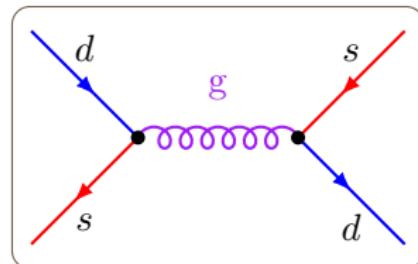
$$\epsilon_K = \frac{\kappa_\epsilon e^{i\phi_\epsilon}}{\sqrt{2}(\Delta m_K)_{\text{exp}}} \text{Im} \langle K^0 | \mathcal{H}_{\text{eff}}^{\Delta S=2} | \bar{K}^0 \rangle,$$

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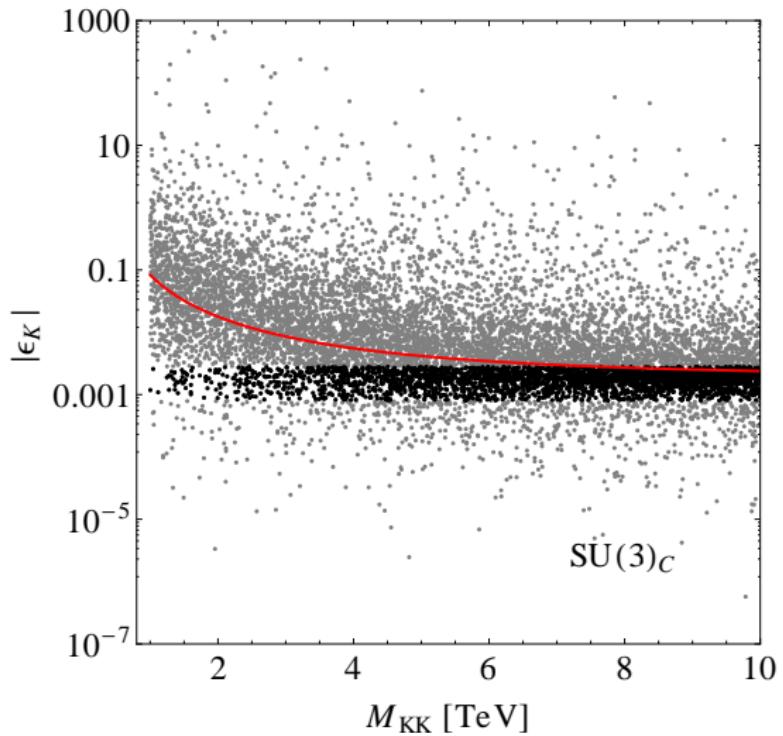


$$\langle K^0 | \mathcal{H}_{\text{RS}}^{\Delta S=2} | \bar{K}^0 \rangle \propto C_1^{\text{SM+RS}} + \tilde{C}_1^{\text{RS}} + 100 \left(C_4^{\text{RS}} + \frac{1}{N_C} C_5^{\text{RS}} \right)$$

$$\langle B | \mathcal{H}_{\text{RS}}^{\Delta B=2} | \bar{B} \rangle \propto C_1^{\text{SM+RS}} + \tilde{C}_1^{\text{RS}} + 7 \left(C_4^{\text{RS}} + \frac{1}{N_C} C_5^{\text{RS}} \right)$$

$$\langle D | \mathcal{H}_{\text{RS}}^{\Delta C=2} | \bar{D} \rangle \propto C_1^{\text{SM+RS}} + \tilde{C}_1^{\text{RS}} + 13 \left(C_4^{\text{RS}} + \frac{1}{N_C} C_5^{\text{RS}} \right)$$

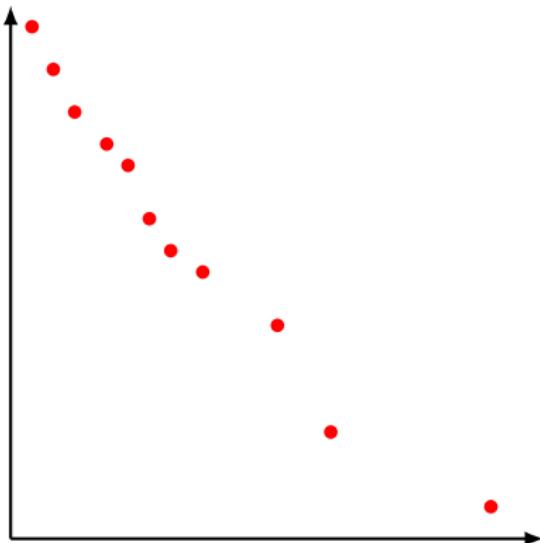
FLAVOR PHYSICS IN THE RS MODEL



FLAVOR PHYSICS IN THE RS MODEL

$$Q_4^{sd} = -\frac{1}{2}(\bar{d}_R^\alpha \gamma^\mu s_R^\beta)(\bar{d}_L^\beta \gamma_\mu s_L^\alpha)$$

Effects in EpsK

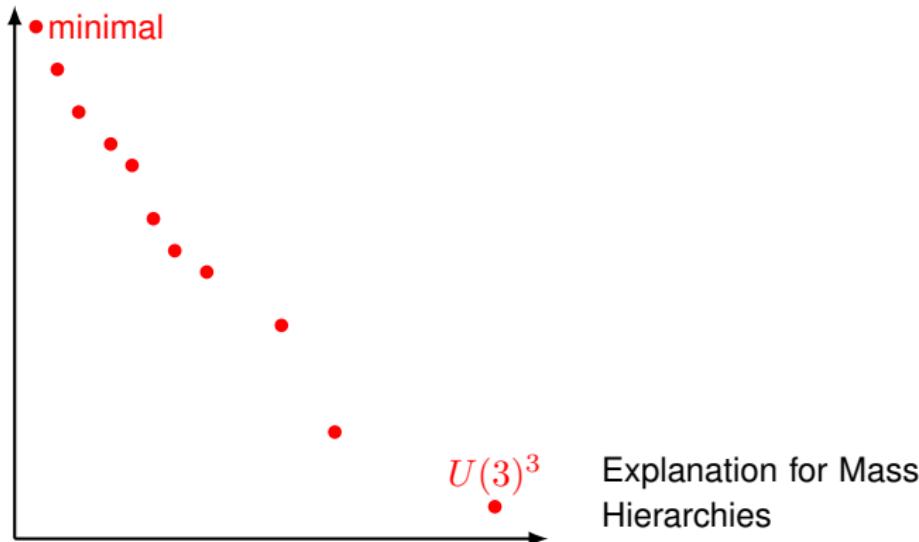


Explanation for Mass
Hierarchies

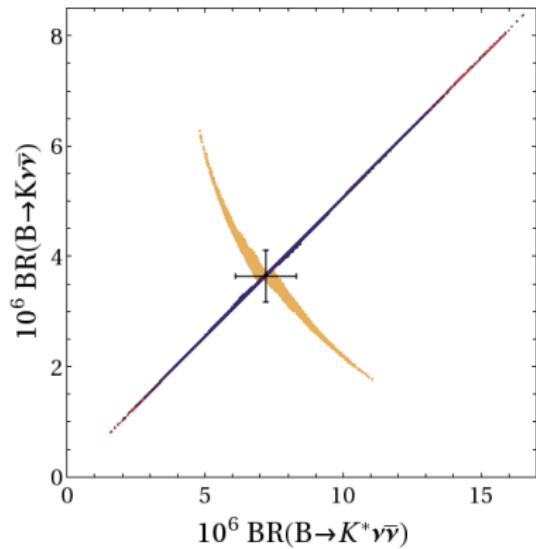
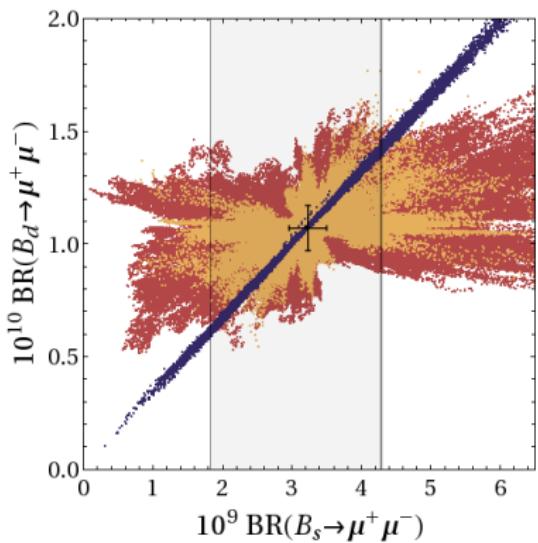
FLAVOR PHYSICS IN THE RS MODEL

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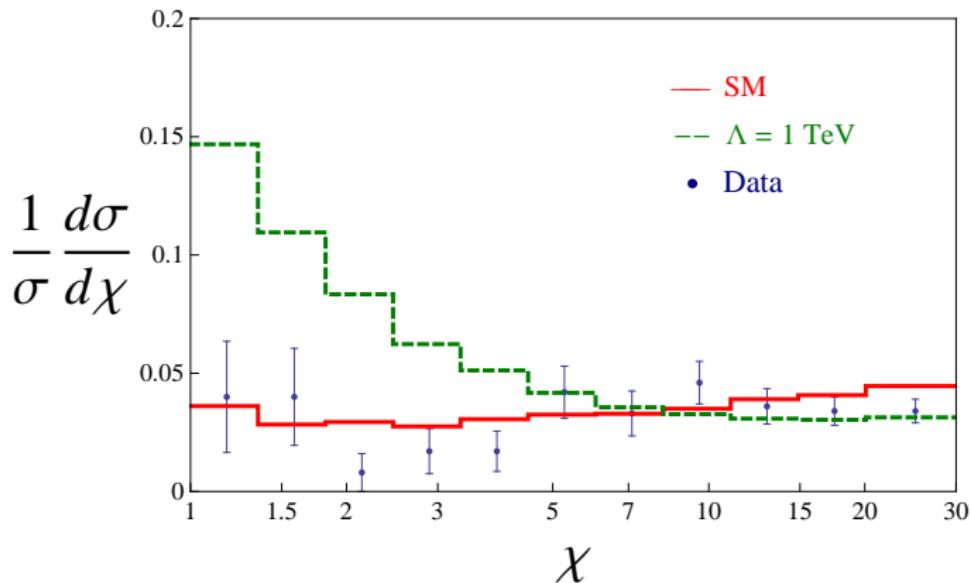


FLAVOR PHYSICS IN THE RS MODEL



[Straub '13]

FLAVOR PHYSICS IN THE RS MODEL



[Pomarol '12]